

# A COMPENSATION BASED BIT-ERROR-RATE ESTIMATION FOR CONVOLUTIONALLY ENCODED TRANSMISSIONS IN WIRELESS SYSTEMS

## CROSS-REFERENCE TO RELATED APPLICATIONS

5           Related subject matter is disclosed in the co-pending, commonly assigned, U.S. Patent applications of Rege, entitled "A Non-Adaptive Symbol Error Count Based Technique for CDMA Reverse Link Outer Loop Power Control," Application No. 09/052581, filed on March 31, 1998; and "An Adaptive Symbol Error Count Based Technique for CDMA Reverse Link Outer Loop Power Control," Application No. 10   09/052696, filed on March 31, 1998; and the co-pending, commonly assigned, U.S. Patent application of Monogioudis et al., entitled "Bit Error Rate Based Reverse Link Outer Loop Power Control with Adaptive Compensation," Application No. 09/514608, filed February 28, 2000.

## FIELD OF THE INVENTION

15           This invention relates generally to communications and, more particularly, to wireless systems.

## BACKGROUND OF THE INVENTION

Many of the bearer services that will be available over 3G (Third Generation) Wireless Systems such as UMTS (universal mobile telecommunications system) use 20   block-based transmissions that, although protected by a Cyclic Redundancy Check (CRC), possess long transmission time intervals (TTI) that make necessary the estimation of bit error probability within the block and before the CRC is checked. As such, to provide some limited error protection these bearer services can employ convolutional or turbo encoding. In addition, these services typically require provisioning a certain 25   Quality of Service (QoS) that is specified in terms of the average Bit-Error-Rate (*BER*) as seen by the end user. To that end, a wireless receiver needs to provide a *BER* estimate from the convolutional or turbo encoded received signal to support these services and their ability to deliver the desired QoS to the end user.

For bearer services employing turbo encoding, it is known in the art that a receiver can provide *BER* estimates for a received signal by using iterative decoding methods based on Maximum A posteriori Probability (MAP) decoders or variants thereof (such as log-MAP, or Soft Output Viterbi Algorithm (SOVA)). These methods produce soft outputs representing the a posteriori log likelihood ratios for the received bits. From these soft outputs, *BER* estimates are computed in a straightforward manner.

In contrast, for those bearer services employing a convolutional coding scheme, there is a need to provide a method and apparatus to estimate the bit error rate – and, therefore, provide the ability to estimate the QoS as seen by the end user.

## SUMMARY OF THE INVENTION

In accordance with the invention, a receiver processes a received signal to generate a Yamamoto-Itoh (*YI*) metric. The receiver provides a Bit-Error-Rate (*BER*) estimate for the received signal as a function of the *YI* metric.

In an embodiment of the invention, a wireless receiver, of a UMTS (universal mobile telecommunications system) based system, comprises a convolutional decoder, a processor and memory. The convolutional decoder processes a received signal and provides a *YI* metric to the processor. The processor (a) retrieves, from a look-up table stored in the memory, a compensation factor as a function of the *YI* metric value provided by the Viterbi decoder; (b) retrieves, from another look-up table stored in the memory, an initial *BER* estimate as a function of the *YI* metric; and (c) modifies the initial *BER* estimate with the retrieved compensation value to provide a *BER* estimate.

## BRIEF DESCRIPTION OF THE DRAWING

FIG. 1 shows a portion of a wireless endpoint embodying the principles of the invention;

FIG. 2 shows an illustrative flow chart embodying the principles of the invention;

FIG. 3 shows an illustrative look-up table for use in the portion of the wireless endpoint of FIG. 1; and

FIGs. 4 – 9 show various graphs.

## DETAILED DESCRIPTION

This description is broken into two parts. The first part describes an illustrative embodiment of the inventive concept. The second part provides material on the analytical basis for the invention for those readers so interested.

#### 1. Yamamoto-Itoh (YI) metric based Bit-Error-Rate (BER) Estimate

FIG. 1 shows a portion of a wireless endpoint 200 embodying the principles of the invention. Other than the inventive concept, the elements shown in FIG. 1 are well-known and will not be described in detail. For example, controller 215 is representative of a stored-program-controlled processor with associated memory (not shown, except for look-up table 220) as known in the art. Also, only that portion of wireless endpoint 200 related to the inventive concept is shown, e.g., other processing by wireless endpoint 200 of a received signal is not described. Further, a detailed description of the receiving and demodulation of a wireless signal is not necessary for the inventive concept and, as such, has been simplified. Except as noted below, it is assumed that the wireless endpoint 200 is a part of a Code Division Multiple Access (CDMA) based (e.g., IS-95, CDMA2000, UMTS) mobile communications system and is in communication with another wireless endpoint (not shown). Wireless endpoint 200 is representative of any wireless device, e.g., a base station, mobile station, etc.).

Wireless endpoint 200 comprises RAKE receiver 205, Viterbi decoder 210, controller 215 and look-up tables 220 and 225. RAKE receiver 205 demodulates a received wireless signal and provides a symbol stream to Viterbi decoder 210. The latter provides a decoded bit stream and Yamamoto-Itoh (YI) metrics 211 associated with the corresponding received frame. (It should be noted that some existing chip sets designed for IS-95 base station receivers include YI metric computations as part of the Viterbi decoder. In fact, in some wireless receivers of the prior art, the YI metric is used to assist in frame selection, i.e., whether the frame is “good” or “bad.”) The YI metric associated with the received frame is the minimum difference between the path metric associated with the path that is ultimately selected (the ultimate survivor!) and the path metric associated with any path that is discarded in comparison to the ultimate survivor at any stage of decoding. Further information on the YI metric can be found in Yamamoto, H.,

and Itoh, K., "Viterbi Decoding Algorithm for Convolutional Codes with Repeat Requests," *IEEE Transactions on Information Theory*, vol. IT-26, no. 5, September 1980. (It should be noted that although shown as part of the Viterbi decoder, the *YI* metric calculation can also be performed external to the Viterbi decoder assuming access to the

5 Viterbi decoder path metrics.)

In accordance with the invention, controller 215 uses the *YI* metric to perform *BER* estimation. At this point, reference should also be made to FIG. 2, which shows an illustrative flow chart embodying the principles of the invention. (The inventive concept is implemented using conventional programming techniques, which as such, will not be described herein.) As noted above, it is assumed that Viterbi decoder 210 calculates the

10 *YI* metrics in step 305. The calculated *YI* metric for a received frame is provided to controller 215, via signal 211. In step 310, controller 215 determines a compensation factor as a function of the calculated *YI* metric. Illustratively, in step 310, controller 215 retrieves an appropriate value for the compensation factor from look-up table 220 via

15 signals 216 (*YI* metric value) and 221 (the retrieved compensation factor value) shown in FIG. 1. In particular, controller 215 uses the *YI* metric value as an index into look-up table 220 for retrieving an associated compensation factor. An illustrative look-up table is shown in FIG. 3. It is assumed that controller 215 suitably rounds the received *YI* metric value from Viterbi decoder 210 to the closest value used in look-up table 220.

20 (Also, illustrative values for compensation factors versus *YI* values are shown in FIG. 9 (described below)). In a similar fashion, controller 215 determines an initial *BER* as a function of the calculated *YI* metric via look-up table 225, in step 315. An illustrative look-up table is shown in FIG. 3. (Also, illustrative values for *BER* versus *YI* values are shown in FIG. 6 (described below)). Finally, in step 320, controller 215 provides the

25 *BER* estimate via signal 219. In particular, controller 215 determines the *BER* estimate in accordance with the following formula:

$$BER \text{ estimate} = (\text{compensation factor } (YI))(g'(YI)),$$

where  $g'(YI)$  represents the initial *BER* estimate derived as a function of the *YI* metric for a frame. It should be noted that although not shown as a separate step, it is assumed that

30 controller 215 computes a (time) average of the compensated *BER* estimate over, e.g.,

several frames. (It should be noted that further modifications could also be made to the above-described method. For example, the two look-up tables shown in FIG. 1 can be combined into one look-up table with multiple entries such that controller 215 simply uses a  $YI$  metric value to index into the look-up table for retrieving associated compensation values and initial  $BER$  estimates. Also, as noted below, the  $YI$  metric value could be used to directly determine the  $BER$  estimate (sans compensation value). In this situation, e.g., the look-up table associates a  $YI$  metric value directly with a  $BER$  estimate (e.g., illustrative values are shown in the graph of FIG. 6, described below).)

Values for the above-mentioned look-up tables (e.g., the mapping of the relationship between compensation factor and  $YI$  metric) can be determined *a priori* either analytically or via simulations (described below).

## 2. Analysis

As is well known, frame based convolutionally encoded transmission are decoded at the receiver using a Viterbi decoder. (For general information on a Viterbi decoder see, e.g., Viterbi, A.J., and Omura, J.K., Principles of Digital Communication and Coding, McGraw-Hill, New York, 1979.) The Viterbi decoder produces as its output the maximum likelihood transmitted sequence. That is, if  $\underline{R}$  is the received frame, then the Viterbi decoder produces the sequence  $\underline{X}$  at its output if the probability that  $\underline{X}$  was the originally transmitted sequence given the received frame  $\underline{R}$  ( $\Pr[\underline{R}|\underline{X}]$ ) is greater than or equal to ( $\Pr[\underline{R}|\underline{Y}]$ ) for all  $\underline{Y}$  in the set of possible transmitted (or input) sequences. In order to simplify receiver implementation, logarithms of probabilities, rather than probabilities themselves, are used as “path metrics” and “branch metrics.” The Viterbi algorithm operates in stages. At every stage, the Viterbi algorithm computes (and stores) the best path (i.e., one with the lowest path metric) leading to every possible state of the encoder. In systems using binary input sequences, the best path ending on a particular state at a given stage is computed by comparing the path metrics of the two possible paths (each of which is the best path up to the previous stage) ending on that state and choosing the one with the better path metric as the survivor at that stage. Let  $s$  and  $r$  respectively

denote the path that is selected and the one that is rejected at state  $k$  during decoding stage  $i$ . Let  $p(s)$  and  $p(r)$  respectively denote their path metrics up to that stage. Clearly, the difference between these path metrics at that stage is  $|p(s) - p(r)|$ . Let  $S$  denote the path that ultimately survives when the decoding process is over so that it is looked upon as the best estimate (in a maximum likelihood sense) of the input sequence from the viewpoint of the receiver. Then, the Yamamoto-Itoh metric associated with the received frame is the minimum difference between the path metric associated with  $S$  at any stage of decoding and the path metric associated with the path that was rejected at that stage. This metric is referred to as the “minimum Yamamoto-Itoh metric” or the *YI* metric.

Further information on the *YI* metric can be found in Yamamoto, H., and Itoh, K., “Viterbi Decoding Algorithm for Convolutional Codes with Repeat Requests,” *IEEE Transactions on Information Theory*, vol. IT-26, no. 5, September 1980. The *YI* metric for a received frame can be calculated with relatively little addition to the complexity of the Viterbi decoder. In fact, many of the chip sets designed for IS-95 base station receivers include *YI* metric computations as part of the Viterbi decoder (e.g., see TIA/EIA/IS-95 Interim Standard, *Mobile Station – Base Station Compatibility Standard for Dual-Mode Wide Band Cellular Systems*, Telecommunication Industries Association, July 1993).

As such, the *YI* metric can be looked upon as a measure of the reliability of the decoding decision since a small value of the *YI* metric indicates a greater likelihood of making a decoding error. Conversely, a large value of the *YI* metric would indicate certain robustness in the corresponding decoding decision. In fact, in some wireless receivers of the prior art, the *YI* metric is used to assist in frame selection, i.e., the “correctness of a decoding decision - whether a received frame is “good” or “bad.” However, we have observed that bit errors are also associated with the correctness of a decoding decision – and, therefore, it is possible to use the *YI* metric as a predictor of the possibility of bit errors in the decoded frame. To accomplish this, it is desired, ideally, to establish the following functional relationship:

$$BER = f(YI), \quad (1)$$

where *YI* is the Yamamoto-Itoh metric associated with a received frame and *BER* is the

estimate of the “instantaneous bit error rate” associated with that frame. Unfortunately, the relationship between the  $YI$  metric and the  $BER$  does not hold in a deterministic manner, on a frame-by-frame basis. This is because even in a fixed environment, such as an Additive White Gaussian Noise (AWGN) channel with a given signal-to-noise ratio ( $E_b/N_o$ ), the number of bit errors in a frame and the  $YI$  metric for that frame are both random variables with less than perfect correlation. Consequently, equation (2), below, shows a different form of equation (1) – where the deterministic relationship is between the average  $BER$  (i.e.,  $E[BER]$ ) and the average  $YI$  metric (i.e.,  $E[YI]$ ):

$$E[BER] = g(E[YI]), \quad (2)$$

where both ensemble averages may be replaced by time averages in a practical implementation. It is hoped that the relationship represented by equation (2) holds in all operating environments characterized by different Doppler speeds and multipath profiles. It may be too much to expect that the relationship represented by equation (2) holds in all operating environments. However, to the extent that the variations that occur in different environments are small, one can use equation (2) with a fair degree of confidence in  $BER$  estimation and control schemes.

One application of equation (2) is in a power control scheme designed to hold the average  $BER$  around a specified target. If  $T_{BER}$  is the desired average  $BER$ , the corresponding average value of the  $YI$  metric (denoted as  $T_{YI}$ ) is:

$$T_{YI} = g^{-1}(T_{BER}). \quad (3)$$

Once the target for the average value of the  $YI$  metric is determined, it can be used in a power control scheme that monitors the local average of the  $YI$  metric (through filtering) and then adjusts the power upward or downward depending on whether the local average is less than or greater than  $T_{YI}$ .

The relationship represented by equation (2) can be determined for use in providing  $BER$  estimation. For the purposes of analysis, it is assumed that the communication system of interest is similar to the downlink of in an IS-95 based wireless system operating at Rate Set 1 which uses a  $\frac{1}{2}$  rate convolutional code with interleaving as specified in TIA/EIA/IS-95 Interim Standard, *Mobile Station – Base Station Compatibility Standard for Dual-Mode Wide Band Cellular Systems*, Telecommunication

Industries Association, July 1993.

A symbol level simulation of this system operating in an AWGN channel was run at different values of the receiver signal-to-noise ratio. The symbol level simulation assumes ideal channel estimation at the receiver. FIGs. 4 and 5 respectively show simulation results for the average (post-decoding) *BER* and the average value of the *YI* metric as a function of the  $E_b/N_o$  measured at the receiver. From these graphs, a plot can be made of  $E[BER]$  as a function of  $E[YI]$  for the AWGN channel. This plot is shown in FIG. 6. It is straightforward to fit a curve capturing the relationship between  $E[YI]$  and  $E[BER]$  as given in FIG. 6. For convenience, this relationship can be approximated with a simple analytic relationship, namely,  $E[BER] = g'(E[YI])$ , where the function  $g'(x)$  is given by:

$$g'(x) = \begin{cases} \exp[\ln 0.5 - x[(\ln 0.5 - \ln 0.118) / 0.0185]], & \text{if } x < 0.0185, \\ \exp[\ln 0.118 - (x - 0.0185)[(\ln 0.118 - \ln 0.00026) / 0.1315]], & \text{otherwise.} \end{cases} \quad (4)$$

The function  $g'(x)$  embodies a simple piecewise linear relationship between the logarithm of the expected value of *BER* and the expected value of the *YI* metric.

Strictly speaking, the functional relationship represented by equation (4) between  $E(BER)$  and  $E(YI)$  has been established by considering the AWGN channel alone. However, it is assumed that this relationship holds good for other channels as well. This assumption is central to using a *YI* metric as a basis for *BER* estimation. In addition, it is assumed that when the Viterbi decoder, after processing a received frame, generates the *YI* metric for that frame, that  $g'(YI)$  is an estimate of the bit error rate for that frame. Thus, the *BER* estimation method using a *YI* metric can be succinctly described as follows.

Whenever the Viterbi decoder at the receiver processes a received frame and produces the *YI* metric for that frame, treat  $g'(YI)$  as an estimate of the *BER* for that frame. Now compute the (time) average of this estimate through a suitable filtering (e.g. a single pole infinite impulse response filtering), or averaging, technique to produce a more robust estimate of the average bit error rate for the desired time-frame. The following mathematical relationship represents the essence of this method:



$$\hat{BER} = \langle g'(YI) \rangle, \quad (5)$$

where  $\hat{BER}$  represents the estimate of the average bit error rate for the desired time frame and  $\langle X \rangle$  represents a time average of the stochastic process  $X$ , computed via suitable filtering or averaging techniques. This method is referred to herein as the “simple BER

#### 5 Estimation Based on the Yamamoto-Itoh Metric.”

Unfortunately, we have determined that the use of the simple BER estimation technique based on the  $YI$  metric overestimates the bit error rate in all environments. One reason for this overestimation is because the simplifications on which the first  $BER$  estimation is based assumes that the functional relationship embodied in “ $g'(\cdot)$ ” (which

10 characterizes the relationship between the average value of the  $YI$  metric and the average value of the  $BER$ ) can be substituted for the relationship that exists between the  $YI$  metric for a frame and the corresponding  $BER$  estimate on a frame by frame basis. However, even in an AWGN environment with a fixed signal to noise ratio ( $E_b/N_o$ ), the  $YI$  metric behaves like a random variable with considerable variation from frame to frame. Also,

15 the relationship between the average value of the  $YI$  metric and the average  $BER$  is highly non-linear. Consequently, it can be observed that even in the AWGN environment the average value of the  $BER$  estimate,  $E[\hat{BER}]$ , calculated using the relationship  $E[\hat{BER}] = E(g'[YI])$ , will be significantly different from the true average  $E(BER)$ , which bears the relationship  $E[BER] = g'(E[YI])$  with the average value of the  $YI$  metric.

20 Therefore, and in accordance with the invention, a compensated  $YI$  metric based BER estimation is used to account for the effect of the variation of the  $YI$  metric and the non-linear relationship between  $E(BER)$  and  $E[YI]$ .

This is done as follows. Once again, it is assumed that the communication system is operating in an AWGN environment with the  $E_b/N_o$  held constant at, say,  $w$  dB. For a

25 given value of  $w$ , the average values of the  $BER$  and the  $YI$  metric can be determined from FIGs. 4 and 5, respectively.

The relationship (seen in FIG. 5) between the  $E_b/N_o$  represented by the variable  $w$  and the mean value of the  $YI$  metric can be approximated by the piecewise linear function

$h'(w)$  given below:

$$h'(w) = \begin{cases} 0.0515 + (w - 1.072) / 15.25, & \text{if } w > 1.072, \\ 0.0185 + (w - 0.103) / 29.36, & \text{if } -0.293 < w \leq 1.072, \\ 0.005, & \text{otherwise.} \end{cases} \quad (6)$$

Turning now to FIG. 7, this shows the standard deviation of the  $YI$  metric as a function of the  $E_b/N_o$  for AWGN channels. The relationship depicted in FIG. 7 is approximated by the piecewise linear function,  $k'(w)$ , given by:

$$k'(w) = \begin{cases} 0.0505 + [0.0007(w - 2.041) / 0.792], & \text{if } w > 2.041, \\ 0.0401 + [0.0104(w - 1.072) / 0.969], & \text{if } 1.072 < w \leq 2.041, \\ 0.0205 + [0.0196(w - 0.103) / 0.969], & \text{if } -0.169 < w \leq 1.072, \\ 0.015, & \text{otherwise.} \end{cases} \quad (7)$$

The last conditions in equations (6) and (7) are equivalent to placing a floor on the lowest values that  $h'(w)$  and  $k'(w)$  can respectively take.

The functional relationships given in equations (6) and (7) are used to determine the mean and the standard deviation of the  $YI$  metric when the  $E_b/N_o$  is held at  $w$  in an AWGN channel.

From equations (6) and (7), the mean value and the standard deviation of the  $YI$  metric can be determined for any given value of the  $E_b/N_o$  for the AWGN channel, yielding a two parameter characterization of the stochastic nature of the  $YI$  metric. With this two-parameter characterization for any given value of the  $E_b/N_o$ , say  $w$ , any suitable family of probability distribution functions (PDFs) that are amenable to two-parameter characterization can be used to approximate the PDF of the  $YI$  metric. Since the Yamamoto metric can never be negative, one of the properties of any applicable family PDFs is that they should have no probability mass below zero.

Illustratively, the non-central Chi-square family of PDFs (with degrees of freedom equal to 2) is used to approximate the PDF of the  $YI$  metric. Consider a random variable,  $Z$ , whose PDF belongs to this family.  $Z$  can be written as:

$$Z = X^2 + Y^2, \quad (8)$$

where  $X$  and  $Y$  are independent and identically distributed Gaussian random variables with mean  $m$  and standard deviation  $s$ . It follows then that the mean,  $m_z$ , and variance,  $v_z$ ,

of the random variable  $Z$  are respectively given by:

$$m_z = 2m^2 + 2\sigma^2 \quad v_z = 8\sigma^2 m^2 + 4\sigma^2. \quad (9)$$

Returning briefly to the simple *BER* estimation procedure described in the earlier section, the error in *BER* estimation that is likely to occur can be determined as follows.

- 5 Recall that this procedure assumes that if the *YI* metric computed by the Viterbi decoder after processing a frame is  $z$ , then the local *BER* estimate is  $g'(z)$  where  $g'(\cdot)$  is as given in equation (4). The estimate of *BER* produced by this procedure is given by  $\langle g'(YI) \rangle$ , which is a time average of the quantity  $g'(YI)$ . Assuming certain ergodicity properties, the expected value of this time average is given by:

$$10 \quad E[\langle g'(YI) \rangle]_w = E[g'(YI)]_w. \quad (10)$$

In equation (10), the subscript  $w$  is used to indicate the fact that the expectations have been carried out assuming an AWGN environment with  $E_b/N_o$  equal to  $w$ . Assuming that the *YI* metric has a Chi-square distribution with mean and standard deviation equal to  $h'(w)$  and  $k'(w)$  respectively, the expected value of the *BER* estimate computed by the simple *BER* estimation method can be determined in a straightforward manner:

$$15 \quad E[\hat{BER}]_w = E[g'(YI)]_w = \int_0^\infty f_w(z) g'(z) dz, \quad (11)$$

where  $f_w(z)$  denotes the non-central Chi-square probability density function with mean  $h'(w)$  and standard deviation  $k'(w)$ . (It should be noted that the above integral can be evaluated numerically to any desired degree of accuracy. Chi-square distributions corresponding to different values of  $m_z$  and  $v_z$  can be generated through simulations (as is known in the art) for use in evaluating the above integral.)

- The quantity,  $E[g'(YI)]_w$ , evaluated via the above integral, can be contrasted with the true average value of *BER*,  $E[BER] = g'(E[YI]) = g'(h'(w))$ . The ratio of the true expected value of *BER* and the expected value of the *BER* estimate is denoted by  $r(w)$ :

$$25 \quad r(w) = \frac{g'(h'(w))}{E[g'(YI)]_w}. \quad (12)$$

FIG. 8 shows the behavior of this ratio, when the  $E_b/N_o$ ,  $w$ , is varied over the

range 0 to 4 dB.

In accordance with the invention, if the system is known to operate in an environment where the  $E_b/N_o$  is in the vicinity of some fixed value, say  $w$ , then the *BER* estimate produced by the simple *BER* estimation procedure (described above) is modified so that the expected value of the (modified) *BER* estimate would equal the true expected value of *BER*. This is done simply by multiplying the *BER* estimate  $g'(YI)$  by the compensation factor  $r(w)$ . In other words, when the value of the *YI* metric produced by the Viterbi decoder is  $x$ , instead of treating  $g'(x)$  as the estimate of the local *BER*, the estimate of the local *BER* is given by  $g_w''(x)=r(w) g'(x)$ . It is easy to show that the expected value of this modified estimate equals the true expected value of the *BER* when the  $E_b/N_o$  associated with the AWGN channel is held at  $w$  dB.

In general, the  $E_b/N_o$  level at the receiver hardly stays close to a fixed value. One may, on the other hand, have some idea about the range over which it typically varies. It is assumed that the receiver  $E_b/N_o$  is known to take values in the range  $[W_L, W_H]$ . In that case, the following approach can be taken to compute the compensation factor assuming that the  $E_b/N_o$  is uniformly distributed over the range  $[W_L, W_H]$ .

It is assumed that the *YI* metric produced by the receiver for a given received frame is  $y$ . Now, for a given  $E_b/N_o$  value,  $w$ , it has been assumed that the *YI* metric has a non-central Chi-square distribution with mean  $h'(w)$  and standard deviation  $k'(w)$ . This distribution is represented by the probability density function  $f_w(.)$  as described earlier. Therefore, if the  $E_b/N_o$  level is  $w$ , the probability that the *YI* metric is within the range  $[y, y+dy]$  is  $f_w(y)dy$ . Therefore, since the  $E_b/N_o$  is uniformly distributed over  $[W_L, W_H]$ , the probability that the underlying  $E_b/N_o$  is in the range  $[w, w+dw]$  given that the *YI* metric is  $y$  equals:

$$\Pr[w < E_b / N_o \leq w + dw] = \frac{f_w(y)dw}{\int_{W_L}^{W_H} f_z(y)dz}, \quad W_L \leq w \leq W_H. \quad (13)$$

In equation (13), the function  $f_z(y)$  denotes the Chi-square conditional probability density function of the *YI* metric given that the underlying  $E_b/N_o$  is  $z$  dB. As stated above,

if the  $E_b/N_o$  level is around  $w$ , the compensation factor should be  $r(w)$ . Combining this fact with equation (12) yields:

$$C(y) = \frac{\int_{w_L}^{w_H} r(w) f_w(y) dw}{\int_{w_L}^{w_H} f_z(y) dz}, \quad (14)$$

where the symbol  $C(y)$  denotes the compensation factor to be used if the observed  $YI$  metric for a received frame is  $y$ . In other words, given that the  $YI$  metric for a received frame is  $y$ , the local  $BER$  estimate produced by this method is given by:

$$\hat{BER} = C(y)g'(y). \quad (15)$$

FIG. 9 shows the compensation factor  $C(y)$  as a function of the value of the  $YI$  metric  $y$ .

This method is referred to as the Compensated Yamamoto-Itoh Metric Based  $BER$  Estimation method.

From the viewpoint of complexity, both of the  $YI$  metric based  $BER$  estimation techniques are simple to implement. For a given coding scheme and framing parameters, they would require the implementation of a  $YI$  metric –  $BER$  mapping which can be stored in the form of a look-up table or a procedure implementing a scalar functional relationship.

It should be noted that the  $BER$  estimation techniques presented here are meant for estimating the average bit error rate observed over a long period (e.g., at least 50 to 100 frames). This is not a limitation of the techniques themselves. Rather, this limitation is due to the fact that bit errors are a rather volatile phenomenon so that one needs a long observation period to obtain a relatively stable estimate. In a given operating environment, if one were to obtain a  $BER$  estimate for a relatively short observation period and compare it to the actual bit error rate for that period, one could easily find significant discrepancy between the two even when a sophisticated  $BER$  estimation technique is used. It is only after averaging the bit errors over a long period that one would be able to obtain a good match. This limitation has an important consequence as far as  $BER$  estimate based control schemes are concerned – they will have to be relatively

slow-acting to avoid potential stability problems.

The foregoing merely illustrates the principles of the invention and it will thus be appreciated that those skilled in the art will be able to devise numerous alternative arrangements which, although not explicitly described herein, embody the principles of the invention and are within its spirit and scope. For example, if this scheme is used in a Bit-Error-Rate-based power control loop, it will cause the median of the *BER* estimates to equal the target *BER*. Also, although shown as a separate elements, any or all of the elements of FIG. 1 (e.g., Viterbi decoder 210) may be implemented in a stored-program-controlled processor (such as controller 215).